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Catastrophe Design - Or How To Behave Like a Worm

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Catastrophe Design - Or How To Behave Like a Worm

Abstract

The number of accidents which are caused by the existence of defects in engineering structures can be reduced in two ways,

1. By diminishing the number and size of the defects, either by making the structure more carefully in the first place or by using better inspection methods in service - or by some combination of the two.
2. By designing structures which are inherently safer - that is to say less susceptible to the presence of defects. An 'ideal' structure could be shot full of holes and still not break.

In fact there will always be some defects in every structure for no manufacturing process and no inspection procedure can be perfect. Furthermore defects will accumulate in a structure between inspections due to fatigue, corrosion, accidental impacts, bad servicing, enemy action and so on. This paper is therefore about the philosophy of the imperfect structure. Since Nature has to deal with similar problems - because no plant or animal is perfect - I am making no apology for using analogies and examples from the new and expanding and exciting discipline of biomechanics. That is to say from the science of the mechanical strength of living structures.

Keywords

Nondestructive Evaluation

Disciplines

Materials Science and Engineering

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1. INTRODUCTION

The number of accidents which are caused by the existence of defects in engineering structures can be reduced in two ways,

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First of all I am going to stick my neck out and say that we know almost nothing about designing structures. Of course there are hundreds of text-books on the subject and people like me give the Lord knows how many lectures about the properties of materials and about the strength of what we choose to call 'structures'. But I think that what we-and the text-books - are really teaching is not so much the design of structures as the design of components. Analytical engineers are enormously clever about this and, very often, they can predict the strength of comparatively simple components within a few percent. In the universities, of course, such problems furnish heaven-sent examination questions containing lots of lovely juicy mathematics. Contrariwise, 'design' is difficult to teach and still more difficult to examine.

But real structures - aircraft, bridges, ships and so on - consist of assemblages of components which interact with each other in very complicated ways: too complicated, very often, for the designer to predict with any approach to accuracy. And, in fact, designers are not very good at it. Looking at the question historically - I am speaking of England, but I doubt if the situation was much different in America - airframes designed by the most eminent designers and stressed by the most experienced teams of stressmen have failed initially on the test-frame at loads which have varied, quite randomly, between rather less than 50% and rather over 150% of the fully factored load. This represents a factor of ignorance or mis-design of something over 3.0. I sometimes think that what keeps aeroplanes in the air is not the skill of the designers but the fact that, to a considerable extent, airframes are designed to stiffness rather than to strength criteria - and the stiffness of a structure is,

of course, much easier to predict than its strength. In other words, if such structures are sufficiently stiff, they will with luck be sufficiently strong.

One cannot really speak of the efficiency of the design process with things like ships and bridges because these structures are almost never broken under controlled laboratory conditions - which is perhaps as well for the reputation of their designers for it is reasonable to suspect that the variation is even greater than it is in aircraft. All we really know is that the number of structural failures in ships and bridges is quite high - and may well be increasing. In other words it may be that we know a good deal about the exact design of components but far too little about putting components together to make complicated structures.

Yet, paradoxically, the very ignorance of designers may contribute to the safety of their structures. For, if an inefficient structure reaches the required load on the test-frame it will have failed at its weakest point and it is certain that the rest of the structure is stronger - perhaps much stronger. Thus most of the structure is understressed, perhaps grossly so. Now the length of a critical Griffith defect varies as the reciprocal of the square of the stress and so, over large areas, we can perhaps put up with quite serious defects - we are really only seriously concerned with faults in certain critical regions of the structure. Although we may not know which these regions are, yet statistics are, so to speak, on our side. The more nearly we approach the ideal of a uniformly stressed structure - the 'one-hoss shay' in fact - the more dangerous the situation becomes. Because the one-hoss shay is the aim for which all designers are striving and because in this computer age there is some danger that they might reach it, it seems to me very necessary to consider the problem of reducing the vulnerability of the structure to unavoidable defects.

2. STRUCTURES AS 'SYSTEMS'

The fact that complicated structures are made up of components whose interaction is difficult to predict naturally leads us to look at structures as 'systems'. For one thing 'systems approaches' are very fashionable just now, understandably so, since the success of such methods in non-structural applications has sometimes been remarkable.

But such an approach to the design of structures raises a number of problems. The text-book case of a 'sufficient' structure provides perhaps the simplest example of a structural 'system'. It is equivalent to a chain with a number of links in series where we can hope to know both the mean and the standard deviation of the strength of each link - from which, no doubt, the probability of failure of the whole chain can be calculated. As this will be markedly worse than that of any individual component in the system there is a strong motive to make the structure redundant - that is to introduce several components or elements in parallel. We want to use both a belt and suspenders - and perhaps pieces of string as well - for surely this will be safer?

The reliability of analogous systems in electrical or hydraulic circuitry (about which I know nothing whatever) may or may not be calculable, but it seems to me that the difficulties which arise in calculating the behaviour of a redundant structural 'circuit' are very great. For a start we have the fact, which is well-known to engineers, that redundancy in a structure can, in some cases, be very dangerous. For, if the load distribution in the system is such that one link can be pushed beyond its yield-point while the system as a whole is still within its working range, then, when the load is reduced, this stretched component may be strained back plastically in the reverse direction by reason of the elastic forces of recovery which are stored in the system. Thus high-strain, low-cycle fatigue may be induced in a very short time. I have seen a pressure vessel which failed in this way after only an hour or two in service - as a consequence a man was killed by boiling oil.

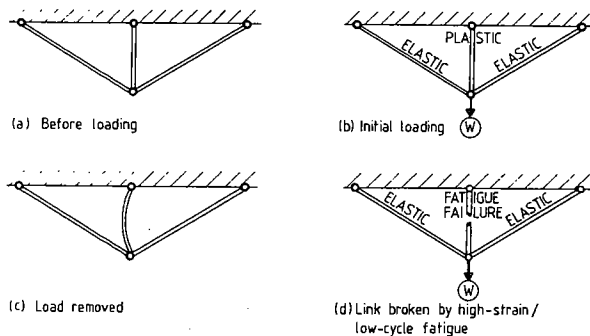


Figure 1: The danger of a redundant structure

3. FRACTURE MECHANICS IS ABOUT COMMUNICATION BETWEEN THE PARTS OF A STRUCTURE

But in reality all structures are redundant, if only because every material contains millions of interatomic bonds a great many of which act in parallel. Or, if we like, we can consider a continuous material, like a metal, as being made up of many parallel elements or strips. As we all know, when a crack starts in a material, the strain energy which is released when one bond or one element breaks is supposed to make its way to the fracture zone where it provides the 'work of fracture', that is the energy which is needed if the breaking process is to be able to continue. This is the Griffith, or 'domino', or 'one thing leads to another' theory of fracture.

In modern engineering structures the accepted way of preventing things from breaking is to use a material with a high work of fracture - hence the use of ductile metals like mild steel. But, of course, this approach almost rules out the use of really strong materials because they are nearly always brittle. Another way of ensuring safety is possibly simpler; it is to prevent the released strain energy from getting access to the fracture zone. In other words to interrupt or to control the elastic communication between the appropriate parts of the system.

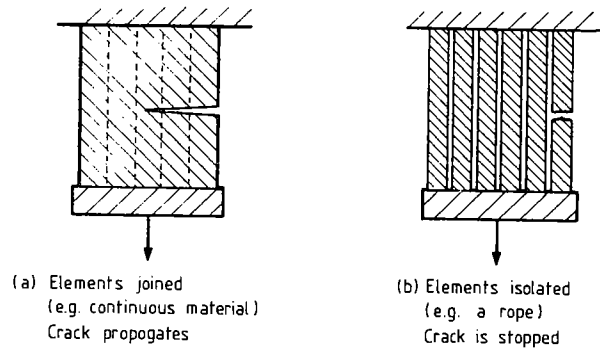


Figure 2: Effect of 'communication' between parts of a structure

This is what commonly happens in ropes and it is what we do in modern suspension bridges. In the older suspension bridges the cables consisted of chains with simple plate links made from wrought iron or mild steel; both of which had a high work of fracture but were consequently quite weak. But in modern bridges the cables are made from many thousands of strands or elements of high tensile steel wire which is very strong but also very brittle. The whole safety of the bridge depends upon the fact that there is virtually no shear connection between the various wires. If one wire breaks its strain energy is released but there is no path by which this released energy can reach the other intact wires and so cause them to break - and so Saint Griffith is frustrated. (Also see Cook & Gordon, 1964, ref. 1). But, if the wires were connected to each other in shear by solder or glue the bridge might become very dangerous; almost as dangerous as if the cable were made from a single solid rod of brittle steel - or indeed of glass.

It is the lack of communication between the elements or components of the bridge which enables brittle high-tensile steel to be used in place of weak, but tough, mild steel - with a very great increase in safety and a very great reduction in weight and cost. Thus we can build, with confidence, bridges from 'dangerous' materials which are around ten times as long as those which can be built from what engineers consider to be 'safe' materials.

At the other end of the scale, if you like, we have monocoque or plate construction which, of course, is particularly fashionable for aircraft and ships. Such metal plates might be considered as an infinitely redundant system of strips or elements which are connected to each other by means of a shear modulus - by virtue of which strain energy can be transmitted from one element to the next. And, as we all know, monocoques tear quite easily - in fact much too easily.

Various intermediate systems can, of course, be made; space-frames for instance. During the war Sir Barnes Wallace's 'geodetic' or lattice construction - used in the Wellington bomber and other aircraft - proved to be exceptionally resistant to damage by 'flak'. And, many years ago, American battleships were fitted with lattice masts - which were supposed to be moderately indestructible by shell-fire. But we cannot entirely escape from Griffith simply by turning a continuous material

into a network or lattice. The problem of 'vulnerability' is not so much a question of whether we use a monocoque or a space-frame as a question of defining and controlling the degree of elastic intercommunication between the various parts of the structure; whether these parts consist of geometrically discrete members, hypothetical strip-like elements in a continuous solid, or interatomic bonds

Thus, in a 'systems approach' to the safety of structures we shall have to be able to:

- (1) Model the elastic interaction which exists between the various units or components in the system.
- (2) Decide what we really mean by a 'unit' or 'component' in the system. Is a single sheet of aluminium, for instance, to be regarded as one single unit or element or as many? If so, how many? I do not see that there can be a rigorous solution to this problem above the atomic or molecular level - but can we approximate, and if so, how?

In fact I do not think that the fracture mechanics of networks has ever been tackled at all seriously. It is clearly very important; but it is also clearly an exceptionally difficult job.

4. PRACTICAL 'SAFE SYSTEMS' IN ENGINEERING AND IN BIOLOGY

4.1 'Uni-directional' systems

The principle of 'isolating' the elements of a structure, that is, making them act independently, is perhaps most easily applied in uni-axial tension; in technology in ropes and suspension bridges. Nature uses this principle in exactly the same way as the bridge-builders when she makes a tendon,

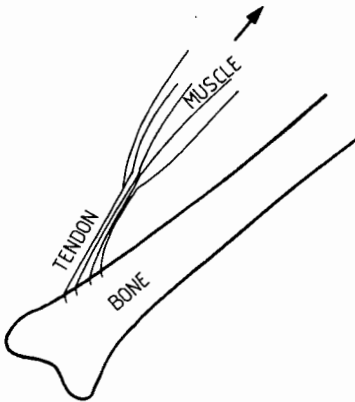


Figure 3

It will be seen that, not only is the middle part of the tendon constituted from many parallel strands of collagen fibre, which are very easily split up or separated - so that there is little or no lateral elastic communication - but that the end attachments are subdivided and multiplied in such a way that the failure of any one joint is not catastrophic - though it is, probably purposely, painful. Nature got there first, but the use of such devices in technology is very old. Rope has been in existence for a long time (it is ruined by gluing the strands together) and, in a more sophisticated way, this approach to safety has been used for the main shrouds of sailing ships at least since Roman times.

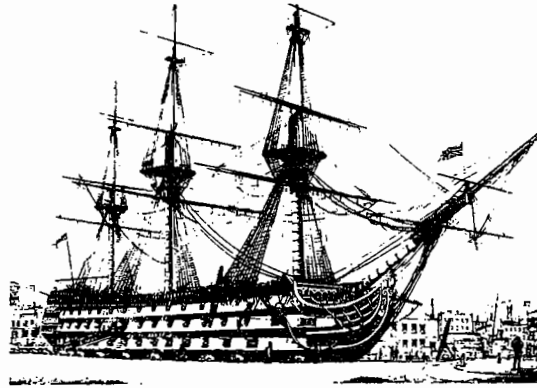


Figure 4: H.M.S. 'Victory'

In compression 'totally isolated systems' are generally impracticable - because of Dr. Euler.

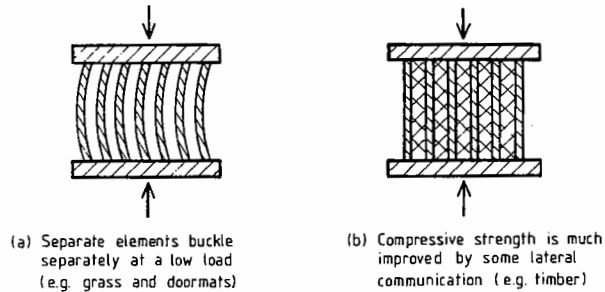
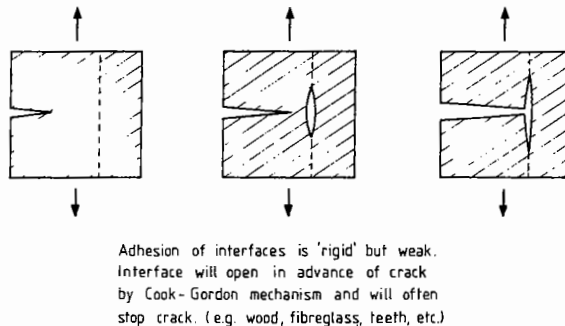


Figure 5: In compression some 'communication' is needed

As a rule lateral communication between the members (e.g. cross-bracing) is necessary in compression structures. Nature uses a 'weak interface' method to ensure the toughness and safety of wood - but it gets Nature into very considerable complications - though in the end Nature wins, hands down. (Cook & Gordon, ref. 1, Jeronimidis & Gordon, ref. 2, ditto, ref. 3). Most fibrous compression systems are provided with 'weak interfaces' and, when we are dealing with weak interfaces we have to distinguish clearly between the strength and the stiffness of the interface,

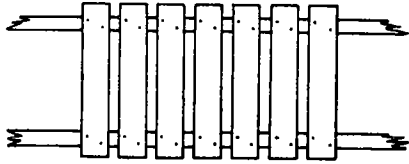


Adhesion of interfaces is 'rigid' but weak. Interface will open in advance of crack by Cook-Gordon mechanism and will often stop crack. (e.g. wood, fibreglass, teeth, etc.)

Figure 6: Effect of 'weak interface' or limited communication

I do not know how this is to be modelled.

When we come to bending the problem is simpler and 'total isolation' of the elements is often beneficial. This of course, is what we do when we make a tiled roof (might it be an interesting exercise for the neophyte to calculate the best size of a roof-tile on 'structural-systematic' principles?). It is also what we do with the decking of simple wooden bridges,



Ordinary slatted decking of simple wooden bridges is example of 'isolated' structure in bending. If one plank breaks little harm is done and damage may not spread.

Figure 7

The aerodynamic surfaces of birds are not constructed from aluminium plates but from many cantilevers made from keratin - in other words feathers. Both the individual barbs on the feathers and also the feathers themselves are only connected to each other laterally in the weakest possible way. Thus the spread of damage is almost wholly prevented and it is quite common to see birds flying about with one or more feathers missing. No doubt the air safety authorities would be horrified.

The isolation of the individual feathers goes a long way to account for the effectiveness of feathers as armour - both on birds and on Japanese warriors. Until the late 1930s the hardened steel armour with which the sides of battleships were protected was mounted on the ship's side rather like tiles on a roof. Intentionally, there was little or no structural connection between the plates.

4.2 Multi-dimensional fibrous systems

The problem of isolating the members or units or cords of a structure is clearly easiest when the applied load is unidirectional - but very frequently this is not the case. Often we have to provide a sheet or membrane of one kind or another which has to sustain, with safety, loads coming from at least two directions. For certain applications cloth is extremely effective. For important engineering uses like sails and the covering of airships - where it is essential to avoid tearing or splitting - cloth provides the only satisfactory solution. One can hardly think of a worse or more dangerous sail than one made from metal foil or sheet. Furthermore, it will be remembered that the loss of the R101 airship in 1931 was due to the improper doping of the covering fabric.

Where the stiffness requirements are more severe the problem becomes more difficult - this is what composites made with glass or boron or carbon fibres are about. The design of these materials is a very sophisticated business. But the same principles, of course, can be applied to metals. I remember that one of the large spherical pressure vessels in the German V2 rocket was made by

winding a kind of ball from high-tensile steel tape the strips being only loosely connected to each other. This was a very clever piece of design which is worthy of imitation.

And Nature does much the same thing when she wants to provide 'rigid' shells; for instance in the cuticle of beetles which are made from crossed layers of chitin fibres, rather badly stuck together by means of a resin-like substance called sclerotin. The shells of shellfish, such as oysters, consist of brittle layers of mineral material separated by weak interfaces.

5. SYSTEMS WITH NON-LINEAR INTERCOMMUNICATION

So far we have dealt with systems where the intercommunication between the parts or elements of the structure is,

- (a) Linear or Hookean - as in modern metal structures. As we have seen such systems are particularly vulnerable and form the foundation of the classical Griffith theory of fracture.
- (b) Systems where the components are almost totally isolated - as with traditional ropes, the cables of modern suspension bridges, natural tendons and so on. Such a system completely frustrates Griffith and is generally very safe indeed, but it is often impracticable.
- (c) Systems containing 'weak interfaces': that is interfaces where the components are 'rigidly' attached to each other initially, but the adhesion fails at a low load. These occur in timber, in teeth and in modern artificial fibre composites.

But none of these systems may be very suitable where what is wanted is a continuous, highly extensible membrane which may have to be watertight or gas-tight.

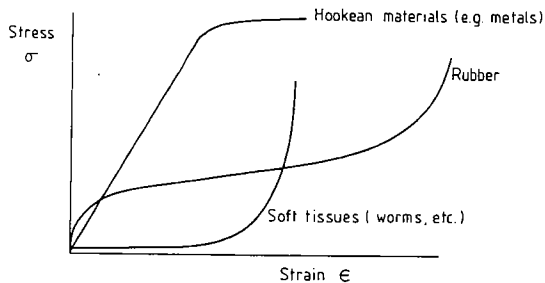
5.1 Natural membranes with non-linear communication systems

This latter requirement is particularly common in animal membranes where, as usual, Nature has at least one very clever trick up her sleeve. Anyone who has ever tried to gut a rabbit with a blunt knife will be aware that skin and stomach membrane and artery walls are curiously difficult to tear - yet there is no question of any weak interfaces in them. Furthermore, if you stick a pin into a blown-up rubber balloon it will burst with a loud pop. If you stick a fish-hook into a worm or a hypodermic needle into a distended human bladder nothing of the sort will happen. There will certainly not be the sort of explosion which occurred when the fuselages of three Comet aircraft disintegrated in 1954.

In the Biomechanics Group at Reading University our first reaction when we became aware of the toughness of animal membranes was to suppose that the work of fracture of these tissues must be very high. But it is not especially so. My colleague, Peter Purslow, has recently measured the work of fracture of a considerable number of animal membranes; it is usually between 10^3 and 10^4 Joules/m². This is perhaps an order of magnitude below the value for aluminium foil which, in comparable thicknesses, tears very easily indeed.

Where rat skin, or worm cuticle, or human arteries differ from metal sheet - or for that matter from

rubber - is not so much in the work of fracture as in the shape of the stress-strain curve,



NOT TO SCALE

Figure 8

Egg membranes and amniotic membranes are exceptions. They have an almost Hookean stress-strain curve, much like a metal, and they tear quite easily, as they are meant to.

But, as far as I know, virtually all tough natural membranes have the J-shaped stress-strain curve indicated in figure 8. This type of curve has two consequences, I think. In the first place it diminishes the amount of strain energy which can be stored in the material at moderate stresses; more importantly, it limits the elastic shear communication which can take place between the various elements or parts of the material.

In a fracture situation we have to remember that, although the stress is high at the stress-concentration, that is at the point of fracture, it is very much lower throughout most of the material. The strain energy which is released to cause fracture is in fact, so to speak, low-grade strain energy, coming from comparatively lightly stressed regions. In predicting fracture therefore we are mostly concerned with the bottom rather than the top part of the stress-strain curve. But, in many animal tissues, the bottom part of the stress-strain curve is almost horizontal and so the shear modulus at low stresses will be very low. In fact, in this region, the material will behave rather like the surface of a liquid, which has surface tension but no shear modulus. In these conditions it will be difficult to transport strain energy from one part of the tissue to the next - so the material will be difficult to tear. Artificial knitted fabrics have the same sort of stress-strain curves as animal tissues (which is why they fit the human body) - they also are very difficult to tear.

Conversely, unreinforced rubber has a high shear modulus at low stresses; thus intercommunication between the elements of a rubber sheet are good and so the rubber is easily torn - even though its work of fracture is high.

In the wild, most animals live more difficult lives than do most engineering structures. They are continually acquiring wounds, scratches, sores, ulcers and all sorts of defects which no aircraft inspector would dream of passing. Of course wild animals die for all sorts of reasons, but they seldom die because dangerous cracks and tears spread from defects in their soft membranes. (The bursting of cerebral aneurysms in human

beings is an exception - we do not understand why. I understand that, as a cause of death, it is virtually confined to human beings living in sophisticated countries).

5.2 Traditional artificial structural systems with non-linear intercommunication

Modern engineers are very apt to look down on traditional artificial structures such as wooden ships fastened with treenails or carts or buggies which are more or less pegged together. These structures creaked and groaned - and wooden ships leaked and leaked - but they practically never disintegrated quite suddenly and without warning like the one-hoss shay or modern monocoque aircraft or welded steel tankers. In fact, according to their lights, these despised traditional structures were very safe. When they did finally disintegrate, it was nearly always the last stage of a long process of attrition. And they gave ample warning.

The safety of these structures depended, paradoxically upon the wobbliness of their joints. A pegged or lashed or sewn joint has a shear stiffness which is non-linear, something like figure 9.

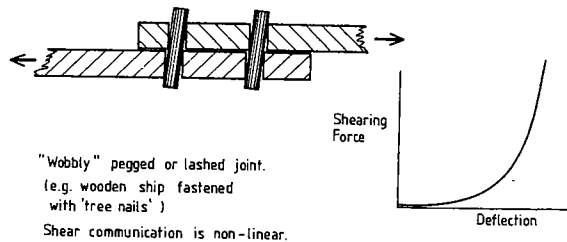


Figure 9

This is very much like the shear stiffness of a natural membrane. Thus a wooden ship, for instance, consists of a system of planks and ribs which are stiff and Hookean in themselves but are connected to each other by non-linear shear connections. The result is a very tough (though leaky) structure and this is no doubt one reason why the world could be explored by incredibly brave men sailing what appear to the modern engineer to be incredibly frail ships. But, if the joints of ships like the Santa Maria had not been wobbly America might not have been discovered until much later.

6. CONCLUSIONS

I think it is fair to say that we do not really understand how to design 'efficient' structures; still less do we know how to minimise the consequences of defects in a structure. It seems to me that there is a good case for doing some sort of 'systems analysis' but,

- (1) It will be difficult to decide what the components or elements of the system consist of.
- (2) It will be essential to model with accuracy the 'elastic communication' between the elements in the system - for this is at the root of the whole question of mechanical failure.

Judging by analogy with traditional structures and with animals a fairly high degree of sub-division will be beneficial. Furthermore it looks to me as though there might be very great advantages in

safety from introducing a non-linear - that is a non-Hookean - connection between the parts of a structure. No engineer, certainly no inspector, could be brought to accept loose or 'wobbly' joints - but is there a case for considering the design of engineering joints with a non-linear response to load? Can all this be explored on the computer?

I am acutely aware that most of what I have said is highly heretical and will perhaps arouse the strongest emotions in many of those present. But let us think for a moment about the conventional engineer's ideal of a respectable modern structure. Broadly speaking this tends to the one-hoss shay and very often to some kind of shell or monocoque. It is true that mathematical analysis often reveals that such structures are lighter and cheaper than what the engineer might consider as Heath-Robinson solutions. But a high proportion of the accidents in the world are caused by mathematicians - not because their mathematics are wrong but because their assumptions are. What the sums about modern structures do not take into account is the interdependence between that unholy trinity, the structure, the material and the defects.

Let us consider the penalties which we incur when we commit ourselves to a conventional modern shell structure made, for instance, from steel. Because of the danger from cracks - that is for reasons of fracture mechanics - we rightly insist on a high work of fracture. In other words we have to use a ductile mild steel. But such a steel is limited to a strength which is probably not much above 60,000 p.s.i. (400 MN/m²) which is about one eighth of the strength of the highest tensile steel and not much over one hundredth of the theoretical strength of iron. But, even so, we do not dare to stress the steel in a large structure to anything like 60,000 p.s.i.; in many cases we probably put a stress-factor of five into our calculations, ending up with a nominal working stress of possibly 12,000 p.s.i. Even so, such structures often break.

What we may hope to do by re-designing our structures on what we might call 'biological' lines is to be able to make profitable use of stronger but more brittle materials while, at the same time, reducing the vulnerability of the structure to defects - thus possibly working without danger at a lower factor of safety with a consequent reduction in weight and cost. Bridge-builders are conservative folk but even they stress their suspension wires to about 85,000 p.s.i. which is about seven times the stress in steel shell structures.

We do not know very much about the factors of safety in animals but, in the few cases in which we can calculate them, they seem to be very low. In one instance, a colleague tells me, about 1.2. Thus, even if the materials used by the animal were worse, specifically, than the materials of the engineer there is a good chance that the animal's structure will be lighter with regard to the service which it has to perform than the engineer's structure. But it must be remembered that many animals also incorporate load-limiting devices of one kind or another.

In fact my respectable friend the worm (with whom I include a great host of soft and wriggly animals) possesses a geodetic structure consisting of a lattice or network of collagen fibres covered by a continuous skin or membrane whose principle virtue is that it does not obey Hooke's law. When such

creatures want a smooth surface they get it by padding themselves out with soft tissue or by blowing themselves up like a motor-tyre.

When Nature wants a more rigid animal she has, of course, to provide a bony framework - that is a skeleton - which is, to some extent, vulnerable. It is noticeable that one of the penalties which animals seem to have to pay for this engineering convenience of brittle bones is an enhanced sense of pain - which has, of course, a protective function.

It can be argued that many engineering structures are designed to pretty exacting stiffness requirements. If we are enabled to reduce the amount of structural material - such as steel - which is needed to provide strength and safety, then we may not be able to provide the necessary stiffness. Since it is much easier to increase the strength than the stiffness of an engineering material this may be a valid objection in some cases.

However, since animals, whether soft or vertebrate, seldom seem to have to provide much stiffness there may be valid biomechanical ways round this difficulty - but that is another story.



"YOU MUST HAVE THIS BRIDGE REPAIRED IN TIME FOR THE PROCESSION NEXT MONDAY. THERE WILL PROBABLY BE ELEPHANTS."

Figure 10

1. COOK, J. & J.E. GORDON (1964). A mechanism for the control of crack propagation in all-brittle systems. *Proc. Roy. Soc. A282*, 508
2. GORDON, J. E. & G. JERONIMIDIS (1974). Work of fracture of natural cellulose. *Nature*, Lond., *252*, 116.
3. GORDON, J. E. & G. JERONIMIDIS (1978). Composites with high work of fracture. *Phil. Trans. Roy. Soc. Lond.* (in press).

SUMMARY DISCUSSION
(J. E. Gordon)

Don Thompson (Science Center): Thank you, Professor Gordon. We have time for a few questions.

Frank Kelley (University of Akron): I wonder if the principles you have mentioned about the nonlinear sheer coupling have been applied successfully in composite structures of filamentary reinforcement module structures in terms of the interaction between the matrix and the fibers. That is, has anyone deliberately put in any connection in order to achieve the results which you suggest through biological membrane?

Professor Gordon: As far as I know, no, but they're only looking at biologic soft tissues on this model. That is to say, in soft tissue, such as an artery wall, there is a very complicated morphology which I think is influencing this area. I haven't time now to talk about some interesting diagrams that can be used to help interpret this cycle, but I don't think it's used in traditional, respectable aerospace circles.

Paul Gammell (Jet Propulsion Lab): How do your composite materials compare with the biological as far as the stress-strains, as far as getting closer to the ultimate tolerances?

Professor Gordon: Well, of course, you better talk to the aircraft structures people. The short answer is, I don't know, but I think we all tend to run composite structures at lower design stresses, perhaps, than metal ones. Perhaps justifiably. If you look at the sort of composite you get in (inaudible) I believe they are now illegal in this country because it was too low. It isn't because you can't make it with (inaudible) I mean, I have seen a plastic sports car that we have now driven into a lamppost which was no bigger than about that. I mean, it's not so much can you do it as will you do it. But I may be wrong about all this.

Dave Kaelble (Science Center): In cases of biological membrane, I would presume the uncoiling of the individual protein chain may be a factor in the stiffening, and it seems to me nonessentially difficult to translate this into a very normal composite-type response, to put the limits on sheer stress transmission.

Professor Gordon: I'm sure it is. Whether you need to do this in a material, I'm not sure because I think the moral is that although the components are more or less (inaudible) against the wood, the communication between is highly (inaudible). I'm not suggesting we should try to get aircraft inspectors to pass wobbly joints. (Inaudible) sources of the assembled intellects of the computer to design communication of joints which are in fact not linear. Conceivably a rubbery glue is a sort of example of this. And of course you get into some extent the sort of woven sticking plaster you put on your cut finger. Incidentally, a thing we ought to go back and look at is skin. This is made from (inaudible) but it was used in enormous quantities in airships as a lining for gas tanks. And it has quite exceptional resistance to hydrogen and helium combined with extraordinary high resistance to tear (inaudible). But this happened 50 years ago, and nobody seems to know anything about it. But it might be worth having a look at.

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